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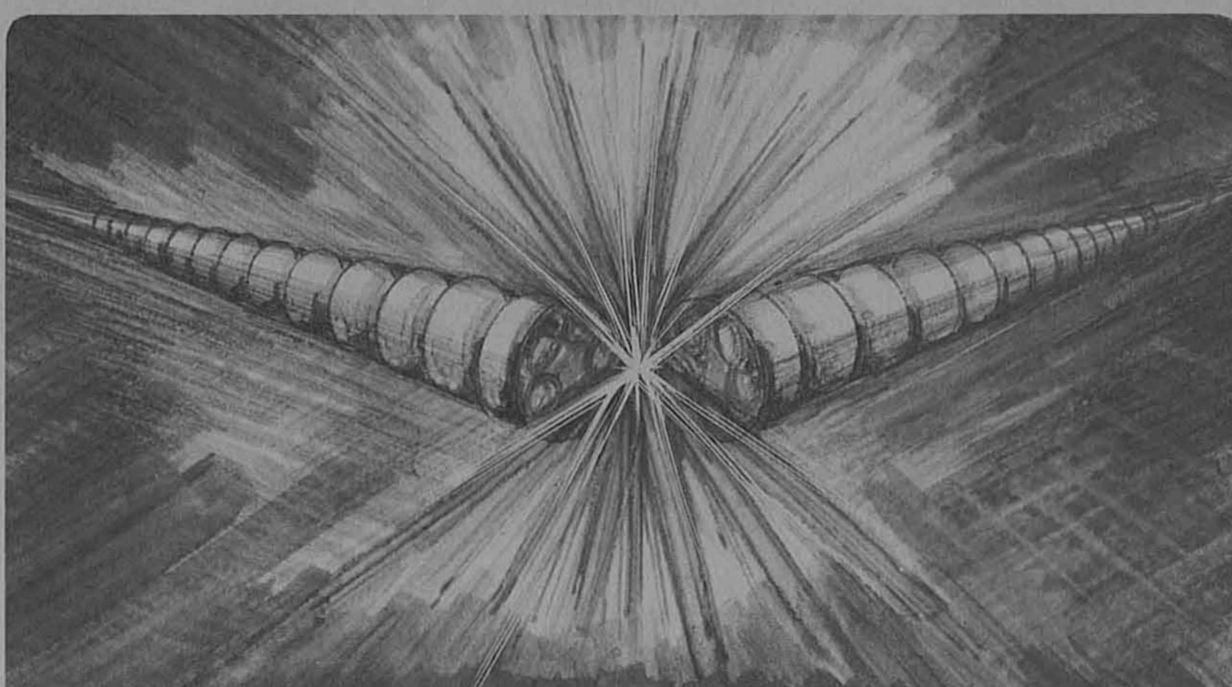

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ABSTRACT

An experimental cabling machine has been constructed and used to investigate the fabrication of a variety of superconducting cables. These include the 23-strand and 30-strand NbTi alloy cables for the Superconducting Supercollider (SSC) and a number of experimental cables. The experimental cables include 24-strands and 36-strands as well as two-level cables with a 6 or 7-strand first level and 23 or 30-strand second level. These results were used to aid in selecting the optimum cable for the SSC dipole and quadrupole magnets. As a result of these studies, cable can now be fabricated to exacting mechanical tolerances (± .006 mm) and with low critical current degradation (2-5%). In addition, tooling design studies have been performed and a Prototype SSC Production Cabling Machine has been designed. The results of the cable optimization studies and the tooling design studies will be discussed. SSC cable production experience on the experimental cabling machine and the production cabling machine will be reported.

INTRODUCTION

The conductor configuration used most often for the fabrication of small aperture, high current density accelerator magnets is a compacted, high aspect ratio cable. This cable evolved from a development program at Rutherford High Energy Laboratory in 1973,[1] and is referred to as a Rutherford-type cable. In comparison to a monolithic conductor, this cable has the following advantages: (1) improved flexibility for ease in bending around the ends of small aperture magnets, (2) potentially higher critical current density (J_c) in NbTi due to the increased cold work range available during manufacture, and (3) reduced losses due to transposition of the strands. With respect to other types of cable, the Rutherford-type cable has the advantages of a high metal density and good mechanical stability, coupled with a minimum amount of degradation of the strands following compaction. Although this type of cable is most often

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used in accelerator magnets, it also has promise for other applications such as rotating machinery.[2] Magnets for several large accelerators, including the Tevatron in the United States, HERA in West Germany, and UNK in the USSR, have been constructed using this type of cable with 23 or 24 strands. This paper describes recent efforts to optimize this type of cable, including improvements in dimensional tolerances, increased number of strands, and reduced critical current degradation during cabling. This work has resulted in the design and fabrication of a new cabling machine, which will also be described.

CABLE REQUIREMENTS FOR THE SUPERCONDUCTING SUPERCOLLIDER (SSC)

The SSC dipoles represent a significant advance in the performance parameters over those used in earlier accelerators such as the Tevatron. In order to reduce the cost of the accelerator, a small bore (40 mm) and a high operating field (6.6T) were chosen. The requirements on field homogeneity are also stringent, and this leads to small dimensional tolerances. These parameters are described in detail in the SSC Conceptual Design Report,[3] and the parameters relevant to the cables are listed in Table I. The dimensional tolerances for the SSC cables are compared with those for the Tevatron and HERA cables in Table II. In order to meet the SSC operating requirements, a high J_c is required. Prior to the SSC project, the state of the art for large production quantities was represented by the Tevatron requirement of $J_c(5T, 4.2K) = 1800\ A/mm^2$. An initial goal of $2400\ A/mm^2$ was established[4] for the SSC wire and an R&D program was undertaken to develop this conductor. Success in reaching and then surpassing this goal[5] led to the decision to increase the J_c value at the time of the SSC Conceptual Design Report to $J_c(5T, 4.2K) = 2750\ A/mm^2$. This goal has also been achieved, and the results are described elsewhere.[6,7] This paper will describe the goals established for the cable and the technology developed to meet these goals.

Table I. SSC Wire and Cable Parameters

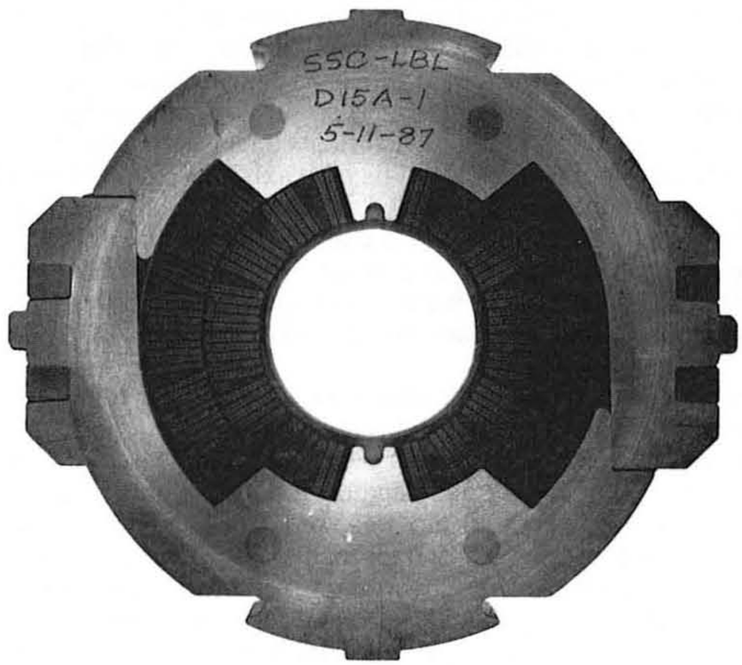
Parameter	Inner	Outer
Wire Diameter	0.81 mm	0.65 mm
Copper to Superconductor Ratio	1.3	1.8
Cable Mid-thickness	1.458 mm	1.166 mm
Cable Width	9.296 mm	9.728 mm
Cable Keystone Angle	1.6°	1.2°

Table II. Dimensional Tolerances for SSC, Tevatron, and HERA Cables

Parameter	Tolerances		
	SSC	Tevatron	HERA
Wire Diameter	±2.5 μm	±7.6 μm	±10 μm
Mid-thickness	±6.35 μm*	±12.7 μm	±20 μm
Width	±25.4 μm	±25.4 μm	±30 μm
Keystone Angle	±0.1°**	±0.4°	±0.2°

*Originally ±12.7 μm **Originally ±.2°

The SSC dipole is a two-layer magnet, with the cross sections of the inner and outer cables chosen so that they can be operated in series with nearly the same critical current and quench protection margins. A 23-strand cable was chosen for the inner layer, since a large quantity (approximately 1.5 X 10^6 m) had been produced for the Tevatron. The copper to superconductor ratio for the inner layer was chosen as 1.3; this value achieves the high overall current density necessary to produce the 6.6T operating field, and at the same time, wire with this ratio is readily manufactured. A value as low as 1.0 had been considered, but earlier experience with winding coils from cables with this ratio, as well as concern about magnet protection following a quench led to the choice of 1.3. A high operating current was achieved by the choice of a 0.8 mm diameter strand. In order to maximize the metal density, the initial cable design specified a fully keystoned cable with a keystone angle of 2.05° for the inner cable. Fabrication trials on cables with this keystone angle showed severe strand degradation in the form of broken filaments and partially fractured strands, so the design was changed to a partially keystoned cable with a keystone angle of 1.6°, and the shapes of the wedge pieces were changed to accommodate this new cable (Fig. 1).



CBB 881-53

Fig. 1. Cross section of a typical SSC dipole magnet with a 40 mm bore and two layers. The inner layer cable has 23 strands and the outer layer cable has 30 strands.

Once the inner layer cable parameters were selected, the outer layer parameters followed from the requirements of (1) operating the coils in series, (2) minimizing the amount of superconductor used in order to reduce the cost, and (3) providing similar protection margins for both coils. The parameters for both cables are shown in Table I. Again, the keystone angle, originally specified as 1.6°, had to be reduced to 1.2° in order to reduce the damage produced at the narrow edge during cabling.

The 30-strand Rutherford-type cable had never before been fabricated in large quantities, so an early goal of the R&D program was to demonstrate that this could be done. Initial attempts to do this on commercially available equipment were not successful; frequent strand crossovers and severe filament breakage, as well as a residual twist, were observed. In order to study these problems in a systematic manner, an experimental cabling machine was designed and constructed at Lawrence Berkeley Laboratory.

RESULTS WITH EXPERIMENTAL CABLING MACHINE

Several aspects of the conventional cabling machine were suspected in the problems with the 30-strand cable, and the experimental machine was developed with these in mind. First, the strand tension was not uniform due to the fact that the machine was constructed with three rotors, each containing up to 12 spools so that some strands traversed a much different wire path than others. Second, the tensioning method relied on the friction developed by a rope in a groove on the wire spool; the friction can vary greatly depending on the spring tension on the rope and on the surface conditions which can change depending on the accumulation of grease or dirt. Third, the mandrel, or core pin, did not provide adequate support for the strands in order to prevent crossovers. The mandrel was an extrapolation of a design described by Gallagher-Daggitt for the fabrication of a 15-strand cable, and while it worked marginally for the 23-strand cable, it failed completely with the 30-strand cable. Finally, the conventional machine could be operated only with fixed spools or with a simple planetary motion of the spools. This violated a principle of Gallagher-Daggitt's original design (Ref. 1), which required that the spools be "supported in a cradle which floats on a rotating frame. This arrangement ensures that each strand is not twisted about its own axis while being formed into a helix, and prevents torsional stress in the resultant cable." The "floating" arrangement described by Gallagher-Daggitt was not found practical for a high speed cabling machine, so a variable planetary system employing a chain drive was designed. In summary, the main features incorporated in the experimental cabling machine were (1) a new mandrel design, (2) improved strand tension control, and (3) variable planetary spool motion.

The new mandrel design replaced the flared end shape with a conical section which tapered smoothly to a thin blade. This shape provides for good wire support over a long distance and thus prevents crossovers. In order to counter the effect of increased drag over a larger contact distance, the mandrel must be fixed rigidly against rotation, highly polished, and well lubricated. With this type of mandrel, both 30 and 36-strand cables have been made at production speeds (4 m/min.) and in long lengths (greater than 1500 m) without crossovers. Improved strand tension control was achieved first by a metal-metal friction device which resembled the tensioning device found on sewing machines. More recently, these devices have been replaced with magnetic hysteresis brakes, which provide excellent tension control, but do not abraid the wire as did the metal-metal friction devices.

The variable planetary spool motion can produce two desirable effects. First, strands which have been twisted prior to cabling can be given a small back-twist in order to remove any residual twist in the cable which may cause problems in coil winding and assembly. Second, strands which are not twisted prior to cabling can be given the twist necessary for reducing eddy current effects in the strands. Further design details of these unique features are presented in an earlier paper.[8]

RESULTS FOR SSC CABLES

A total of 56 km of SSC cable has been produced to date; this includes cable needed to construct model magnets at Lawrence Berkeley Laboratory (LBL), Brookhaven National

Laboratory (BNL), and Fermi National Accelerator Laboratory (FNAL), as well as many short lengths for cabling R&D studies. In the four year period during which this cable was produced, the I_c degradation due to cabling has been reduced and the dimensional tolerances have been improved. Although rectangular cables can be produced with no degradation, a small amount of degradation invariably occurs in a keystoned cable. The evidence for this is obtained from the precise I_c measurements now being made at BNL, where all the cables made in this program have been sent for I_c measurements. In order to evaluate I_c degradation, a number of different measurements are made (see Table III).[9] The I_c values are determined for the strands before cabling and then compared with the cable critical current measured under

Table III. Cable Critical Current Values for Various Measurement Conditions

Note: All measurements are made at a sensitivity of 10^{-14} Ω•m and values are normalized to 4.2 K, 5.6T.

Field Perpendicular To Wide Face		Field Parallel To Wide Face	nX Wire I_c	nX Wire I_c with Wire Self Field Correction	nX I_c For Extracted Strands
High Field Point					
@ thick Edge	@ narrow Edge				
8500	8100	9000	8800	9100	8230

different conditions - all values are reported at a sensitivity of 10^{-14} Ω•m. With the magnetic field applied parallel to the wide face of the cable, the cable I_c value agrees well with the value calculated from the wire measurements when all measurements are corrected for self field effects. With the magnetic field applied perpendicular to the wide face of the cable, different results are obtained depending upon the direction of the sample current. When the current direction is such that the cable self field contribution results in the high field point located at the narrow edge of the cable, the cable I_c values are most seriously degraded. However, when the current is reversed so that the high field point is located at the wide edge of the cable, the I_c degradation is much less. These results, which have been repeated many times, show that the degradation occurs primarily at the narrow edge of the cable, and to a lesser extent at the wide edge of the cable, with little degradation occurring on the wide face of the cable. Similar results were obtained on high sensitivity critical current measurements made on strands extracted from a cable.[10] Severe I_c degradation, e.g., in the range of 15-25% decrease in I_c compared with uncabled strand values, is associated with broken filaments, and so the damage can be observed by etching away the copper matrix. Degradation in the 10-15% range is more difficult to correlate with microstructure; however, serrations of the type shown in Fig. 2 are often observed, as well as occasional broken filaments. Degradation below 10% has not been correlated with any observed defect, but may be associated with the small local reduction in strand area which occurs when the cable is compacted.

The critical current degradation experienced during cabling can be divided into two categories - degradation related to strand properties and degradation related to cabling parameters. Strand properties which affect degradation are: filament uniformity, filament tensile strength, filament position within the composite, and wire diameter. Information on the first three properties is obtained from a sharp bend test, in which the wire is bent back sharply upon itself in a fixture under controlled conditions. The wire is then examined for a crack on the outer diameter, etched and re-examined for broken filaments on the outer diameter. If a wire has properties which are marginal for successful cabling, a crack and/or many broken filaments are observed, and the wire is rejected.

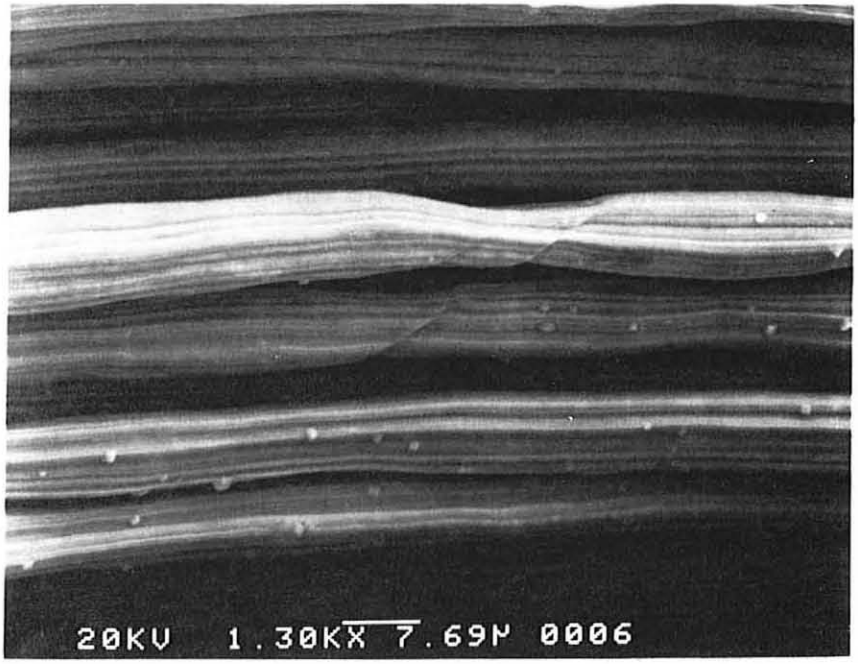


Fig. 2. Longitudinal SEM micrograph of NbTi filaments after the matrix has been removed by etching. Note the serrations on the filaments in the center of the picture. XBB 885-5355

The amount of compaction depends very sensitively on the wire diameter, so the wire diameter must be measured and controlled closely in order to prevent degradation due to over-compaction. The SSC specification requires that the wire diameter be controlled to ± 2.5 μm, and this, in turn, controls the density to less than 1%. Incoming wire is inspected continuously with a laser micrometer to check for conformity.

Cabling parameters which affect the amount of critical current degradation are strand tension, amount of overall compaction, and the stability of the tooling. Strand tension is maintained at less than 10% of the strand tensile strength, and uniform to $\pm 10\%$ for all strands. The amount of compaction and the keystone angle are controlled by precise measurement of the cable dimensions, as described in the next section. The stability of the tooling is maintained by good design practice (rigid mounting of the Turkshead and mandrel) and proper maintenance (replacement of worn bearings or damaged Turkshead rolls). As a check that these conditions are being met, samples of cable are etched to reveal the filaments. Evidence of broken filaments is an indication that the critical current will be seriously degraded, and cabling is stopped until the cause is identified. The final verification is a measurement of the cable critical current; however, these results are typically not available for one week, so the visual observations described here are useful in deciding whether to continue the cabling operation.

At the beginning of the SSC cabling studies, the parameters listed above were not completely understood or controlled, and the critical current degradation was typically about 15%.[11] This is comparable to the value of 13.4% reported for the production series of cable made for the CBA project.[12] At present, with improved wire and better control of the cabling parameters, the I_c degradation is typically less than 8%, based on the following, rather stringent definition of critical current. The strand and cable critical currents both are measured to a sensitivity of 10^{-14} Ω•m and the results are corrected for self-field effects. The degradation is then obtained by comparing the value of the average wire I_c times the number of strands, with the cable critical current obtained with the field perpendicular to the cable wide face, and the high field point located at the narrow edge of the cable.

CONTROL OF CABLE DIMENSIONS

As mentioned above, precise control of cable dimensions is important if I_c degradation is to be minimized. Equally important, close control of cable dimensions is necessary in order to meet the high field uniformity required for the dipole magnets. The initial requirements for the SSC cable dimensional tolerances were set equal to those required for the Tevatron cable (see Table I). However, the smaller bore (4 cm for the SSC compared with 5 cm for the Tevatron) means that the field homogeneity is more sensitive to conductor position, so that the dimensional tolerances should be smaller for the SSC dipoles. A development goal for the SSC cable was to reduce the dimensional tolerances on the cable mid-thickness and keystone angle by a factor of 2, since these are the dimensional parameters which most affect field homogeneity. This requires reducing the mid-thickness tolerance value to ±6.35 μm and the keystone angle to

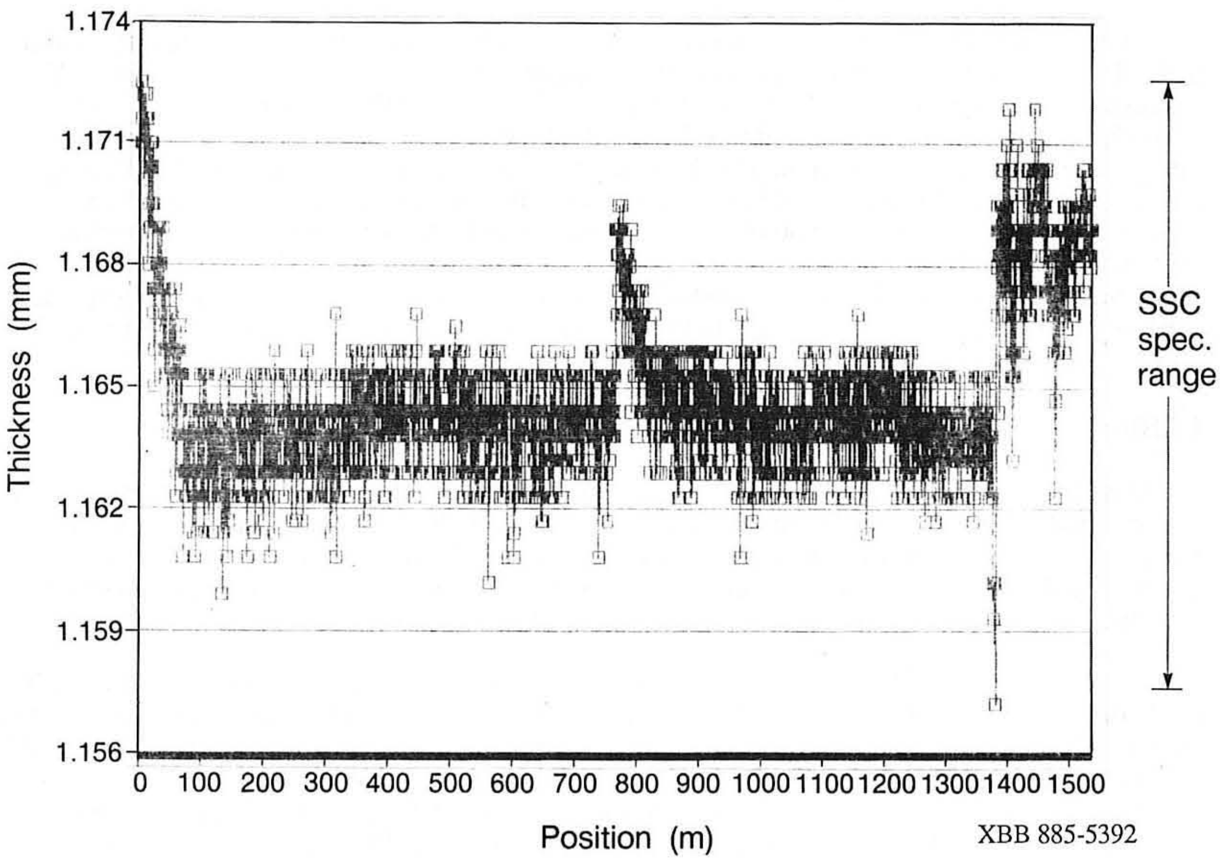


Fig. 3. Cable thickness as a function of position along a cable measured with the on-line cable measuring machine. The excursions which occur at the beginning, at 800 m and at 1400 m, are due to changes in Turkshead roll temperature.

±0.1°. At the beginning of the project, efforts to meet these goals were hampered by the absence of a method for determining the cable dimensions on-line.

Development of on-line measuring technology was begun at FNAL, and the first three measuring machines[13] were completed in 1987. These machines are installed on the cable manufacturing lines and provide periodic measurements, under a specified vertical and lateral pressure, of the cable thickness, width and keystone angle. The precision to which these measurements can be made are: width ±1 μm, thickness ±.05 μm, and angle to ±.01°.[13] With the aid of these on-line measurements, SSC cables are now being made to high dimensional tolerances, and the specification range has been reduced to ±6.35 μm for the mean thickness and ±0.1° for the keystone angle; the standard deviation for the cable thickness for a typical 1500 m length is 2.5 μm. The factor which at present is producing the largest changes in cable dimensions during manufacture is the temperature of the Turkshead rolls. At the beginning of a run, the rolls and frame are the same temperature. As the rolls heat up relative to the frame, the cable thickness decreases, as shown in Fig. 3. During this particular run, cabling was stopped at approximately 800 m and then again at 1400 m. Upon restarting, the thickness is at first larger and then returns to the former value as temperature equilibrium is reached. Work is in progress to attempt to control cable dimensions by controlling Turkshead roll temperature via a feedback system.

DEVELOPMENT OF THE SSC PRODUCTION CABLING MACHINE

At this point, it has been demonstrated that cable can be made in the required lengths and to SSC dimensional specifications. In order to demonstrate further that the SSC cable can be manufactured in industry at the rate required for the SSC project (70 million feet over a 4-year period), a production cabling machine is being developed. This machine incorporates the new design features developed with the R&D cabling machine, i.e., mandrel design, magnetic hysteresis tension controls, and variable planetary spool motion. Furthermore, this machine is designed to produce cable at a rate of 10 m/min. and to include an electronic data acquisition system which will facilitate the record keeping and quality assurance tasks. This cabling machine is being installed in a cable manufacturing plant and will be used to produce SSC cable starting in August, 1988. The design and construction of this machine will be described in another publication.[14]

FABRICATION OF OTHER CABLES

In addition to the standard SSC cables, a number of other cables have been fabricated. The first production lengths of a 36-strand cable have been completed in collaboration with FNAL and are being used to produce high gradient quadrupoles for installation at the Tevatron. This cable is made from 0.53 mm diameter wire and is 9.8 mm wide with a mean thickness of 0.9 mm and a keystone angle of 1.09°. The average I_c degradation during cabling is about 4%.

A series of two-level cables have also been made. These typically contain a first level sub-cable of 6 or 7 strands and a second level of 23 or 30 sub-cables. This type of construction has been used to produce a fine-filament conductor (filament size of 1 to 2 μm) from standard SSC billet extrusions containing about 8000 filaments. When the sub-cables are filled with solder (95 wt% Sn, 5 wt% Ag), the resulting two-level cables are stable against collapse, yet flexible enough for coil winding. The principal drawback to this approach is the additional strand fabrication costs due to more wire drawing and a tendency for more wire breaks at the finer wire sizes. However, this type of cable may find use in 50-60 Hz applications.

CONCLUSIONS

1. The technology for fabrication of Rutherford-type cables has been improved so that 30 and 36-strand cables can now be made in production quantities.
2. Improvements in tooling, coupled with in-line measurement capability, has led to an improvement in dimensional tolerances for the SSC cables by a factor of 2 over that obtained for recent projects (Tevatron and HERA accelerators).
3. A new cabling machine capable of meeting the needs of the SSC project has been designed and built using the results of this R&D program.

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